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Parafoveal preview benefit in reading is not cumulative across multiple saccades

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Abstract

Two empirical predictions can be generated from recent parallel processing models of eye movement control in reading concerning the phenomenon of parafoveal preview benefit. These predictions derive from the assumption that lexical activation accumulates across more than one saccade. A large corpus of eye movement data was used to determine whether parafoveal preview benefit of a target word is modulated by (1) its distance from the penultimate fixation, and (2) the amount of time it spends in the 'perceptual span'. There was an unexpected inverse relationship between first fixation duration and distance: fixations were longer the closer the penultimate fixation was to the target word, and a positive relationship between fixation duration and time: fixations were longer the greater the summed durations of the ultimate and penultimate fixations. These findings represent a challenge for computational models of eye movements in reading.

Keywords: Reading; Fixation duration; Preview benefit

1. Introduction

An important, highly robust finding in reading research is *parafoveal preview benefit*: fixation durations are shorter when parafoveal visual information about the currently-fixated word was available on the previous fixation than when it was denied (see Rayner, 1998, for a review), suggesting that some level of preprocessing of the current word (word *n*) occurred when the eyes were fixating word $n-1$. There is also a positive linear relationship between mean fixation duration and the eccentricity of word *n* from the previous fixation position [1]; this Saccade Distance Effect (Radach & Heller, 2000; Vitu, McConkie, Kerr, & O'Regan, 2001) has been explained in terms of decreasing visual acuity from the centre of the fovea outwards: the further away the previous fixation, the more degraded the visual information, and therefore the less preprocessing possible (Vitu et al., 2001).

Two recent computational models of eye movement control in reading (SWIFT: Engbert, Longtin, & Kliegl, 2002; and Glenmore: Reilly & Radach, 2003) account for preview benefit by assuming that the processing of words within the perceptual span occurs in parallel. Both models incorporate the concept of *lexical activity* (or activation) to represent the degree of processing attained. The activity levels of both foveal and parafoveal words are determined by their eccentricity (reflecting visual acuity constraints; activation rises more slowly with increasing eccentricity) and time (activation increases as a function of time in the perceptual span; the longer the fixation, the greater the activity level). In Glenmore,

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[1] In a large-scale correlational analysis of six subjects reading text passages, Rayner and McConkie (1976) found essentially no relationship (Pearson *r*s ranged from −0.041 to 0.108) between progressive saccade amplitude and the duration of the fixation ending the saccade.

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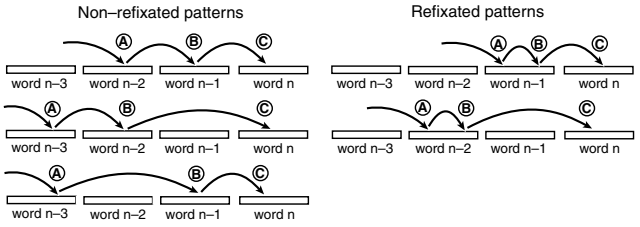

Fig. 1. The five fixation patterns selected for analysis from the Dundee corpus.

activation of a word's representation rises until a saccade is triggered targetting that word; in SWIFT, activation rises until a threshold level is reached after which activation decreases. Generally speaking, for both models variation in processing benefit due to parafoveal preview is attributed to variation in activation levels.

The well-specified mechanisms of these computational models permit specific empirical predictions to be made. Given a sequence of three fixations (A, B and C; see Fig. 1), two predictions can be derived from the assumptions that parafoveal preview benefit is proportional to lexical activation, and that activation levels directly depend on the parallel processing of the words occurring within the perceptual span. First, preview benefit for the word upon which Fixation C falls (the *target* word) should be greater when its distance from Fixation A is short, compared with larger eccentricities (all else being equal). Second, preview benefit for the target word should be modulated by the amount of time the target is located within the perceptual span; thus, the duration of Fixation C should decrease as the summed duration of Fixations A and B increases, but only when Fixation A is close to the target. [2] With respect to the first prediction, there should be an increase in the duration of Fixation C as the distance of the target from Fixation A increases. If preview benefit does not accumulate across successive fixations, then there should be no relationship between eccentricity and Fixation C duration.

Empirical support for the modulation of preview benefit by time is provided by a study by Schroyens, Vitu, Brysbaert, and d'Ydewalle (1999); using a reading-like task, they found that preview benefit effect size increased with the duration of the previous fixation (but see White, Rayner, & Liversedge, in press, for contradictory evidence from a sentence reading study). This paper reports the results of testing the above two predictions using a large eye movement corpus.

An important constraint on the observation of parafoveal preview effects is the size of the perceptual span. Using a eye-contingent display-change technique, McConkie and Rayner (1975) showed that perturbing the text beyond 14–15 characters to the right of the currently fixated character had no reliable influence on reading speed. Thus we can assume that the effective spatial window in which any modulation of preview benefit due to eccentricity could be observed is bounded by the perceptual span size. Note that in studies of eye movements in reading it is appropriate to measure the size of the perceptual span and eccentricity in character spaces; for instance, Morrison and Rayner (1981) demonstrated that mean saccade amplitude was constant over a range of viewing distances when measured in character spaces as opposed to visual angle.

2. Methods

As a source of reading data I utilised the Dundee English corpus (Kennedy, 2003), which consists of the eye movement data collected from 10 readers each reading approximately 50,000 words of newspaper text. Readers' eye movements were recorded using a Dr Bouis Oculometer eyetracking instrument. The position of the right eye was sampled every millisecond. The viewing distance was 500 mm and one character subtended approximately 0.3° of visual angle.

Data matching five common fixation patterns involving three successive forward saccades over two to four words (see Fig. 1) were extracted from the Dundee corpus. Constraints on data selection ensured that there was no intervening punctuation between critical words; the launch word (the word receiving Fixation A) was not the first word on the line of text, Fixation A was at least the second fixation made on the line, the target word (the word receiving Fixation C) was between four and seven letters in length, and the eccentricity of the target from Fixation A was 15 character spaces or less. After selection, 15,116 cases were available for analysis.

3. Results and discussion

Prediction (1), that preview benefit for the target word will be greater the nearer the penultimate fixation, was tested by varying the eccentricity of the target word from the penultimate fixation (Fixation A). If preview benefit is cumulative across saccades, then fixations on the target should be shorter the closer the penultimate fixation, because the target would have a greater chance of being preprocessed. Fig. 2 displays the mean duration of the first fixation on the target word (Fixation C) as a function of the eccentricity of the target from Fixation A (ECC_A), holding the eccentricity of the target from Fixation B small and constant ($ECC_B < 5$ character spaces), for four target word lengths. It was important to control

[2] This interactive prediction is similar to the assumption of the SWIFT model (Engbert et al., 2002) that lexical activity is a multiplicative function of time and eccentricity.

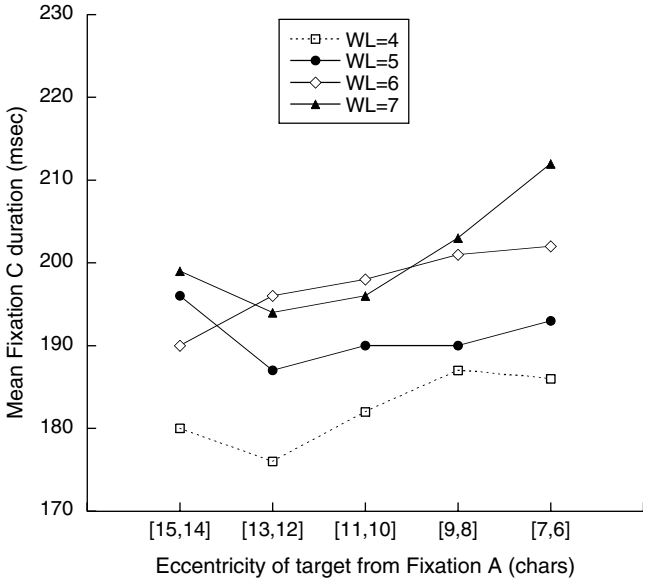

Fig. 2. Mean first fixation duration on the target word (Fixation C) as a function of the eccentricity of the target from Fixation A, plotted separately for words of lengths four through seven letters. Each plot point represents on average 820, 758, 675 and 642 cases, for the 4, 5, 6, and 7-letter words, respectively.

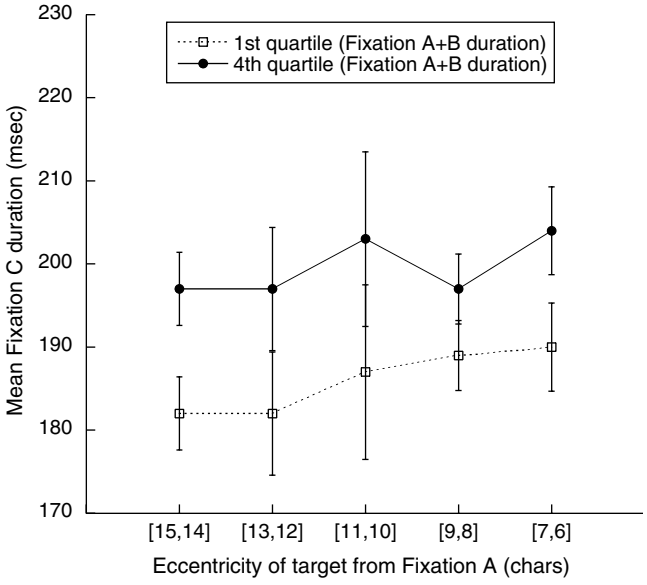

Fig. 3. Mean first fixation duration on the target word (Fixation C) as a function of its eccentricity from Fixation A and the summed duration of Fixations A and B (data for 4–7 letter words are collapsed together). Each plot point represents an average of 718 cases (per participant average $n = 84$; range = 22–174). Bars indicate within-subject 95% confidence intervals, computed as recommended by Loftus and Masson (1994).

the eccentricity of the target from Fixation B as it is probably the strongest determinant of preview benefit (e.g., Kennison & Clifton, 1995). For all four word lengths, the trend is opposite to the expected direction: First fixation duration (FFD) on the target word tends to *decrease* as eccentricity from Fixation A increases, or conversely, FFD tends to increase as eccentricity from Fixation A decreases.

Prediction (2), that preview benefit for the target word will be modulated by the amount if time it is located within the perceptual span, was tested by computing FFD on the target word as a joint function of its distance from the penultimate fixation and the amount of time the target is assumed to spend in the perceptual span (estimated as the summed durations of Fixations A and B), again holding the eccentricity of the target from Fixation B constant ($ECC_B < 5$). Data for target words of lengths four through seven letters were collapsed together. Quartiles were computed for each participant individually for each eccentricity bin, and the mean duration of Fixation C was computed for the extreme quartiles and averaged across participants. Values for a given participant/eccentricity bin combination containing fewer than 20 cases were not included in the mean. The mean summed duration of Fixations A and B was 301 ms and 527 ms for the first and fourth quartiles, respectively.

Fig. 3 demonstrates the same linear relationship between ECC_A and FFD illustrated in Fig. 2. In addition, there is a clear effect of the summed duration; contrary to predictions, the larger the summed duration of Fixations A and B (i.e., the *more* time the target word spends in the perceptual span), the *longer* the FFD on the target, or conversely, the smaller the summed duration of Fixations A and B, the shorter the target FFD. This effect does not appear to interact with eccentricity; there is no evidence for the predicted facilitation at the smaller eccentricities. The effect cannot due to a confound with interindividual differences in fixation duration, as across-participant means were computed. However, it may be explainable as a 'spillover' effect from Fixation B: if processing of the word upon which Fixation B falls is in some sense difficult, then Fixation B will tend to be longer than normal, with processing 'spilling over' to the next fixation, thus inflating the duration of Fixation C (e.g., Rayner & Duffy, 1986). [3]

In order to show just the relationship between the durations of Fixation B and Fixation C, Fig. 4 plots FFD as a joint function of ECC_B and the extreme quartiles of the duration of Fixation B, collapsing together 4- through 7-letter target words. Values for a given participant/eccentricity combination containing fewer than 20 cases were excluded. As well as confirming the Saccade Distance effect (the linear relationship between eccentricity and fixation duration) for this data, Fig. 4 indicates that the 'spillover' effect from Fixation B is constant over the full range of eccentricities; there is

[3] Reduced parafoveal preprocessing rate due to a high foveal processing load is an alternative view.

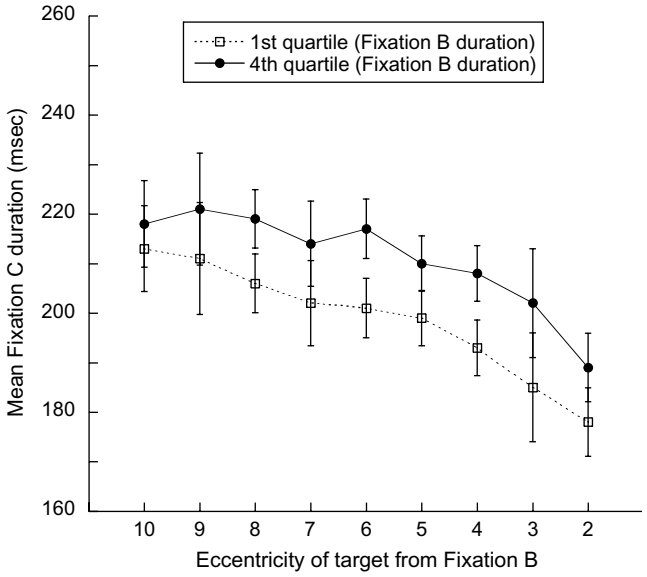

Fig. 4. Mean first fixation duration on the target word (Fixation C) as a function of its eccentricity from Fixation B and Fixation B duration (data for 4–7 letter words are collapsed together). Each plot point represents an average of 1039 cases (per participant average $n = 106$; range = 23–242). Bars indicate within-subject 95% confidence intervals.

no evidence for increased preview benefit as a function of time, even for the smallest eccentricities. [4]

It is possible the effect of the summed duration of Fixations A and B apparent in Fig. 3 is actually due to the duration of Fixation B only. Repeated-measures multiple regression can address this question; by partialling out Fixation B duration, any unique influence of Fixation A duration on the duration of Fixation C can be isolated. This procedure involved computing regression equations including five predictor variables separately for each participant, and then for each predictor testing the null hypothesis that the regression coefficient did not reliably differ from zero using one-sample t tests (this method appropriately removes variance due to participants; see Lorch & Myers, 1990). Table 1 supplies the across-participant mean of the unstandardised regression coefficients and associated t-statistics and p-values, for the five predictor variables. All five factors were significant: the length of the target word, the eccentricity of the target from both Fixation B and Fixation A (although the latter is a much smaller effect), and the durations of both Fixation B and Fixation A (again, the latter effect is much smaller).

To summarise the results of the first regression analysis (presented in the upper part of Table 1): given a sequence of three fixations separated by progressive saccades, when the target word is located no more than four character spaces from the second fixation, FFD on the target increases an average of 11.0 ms per character of eccentricity from Fixation B (depicted in Fig. 4), and decreases an average of 2.8 ms per character of eccentricity from Fixation A (consistent with Figs. 2 and 3). Target FFD also increased an average of 10.1 ms per 100 ms of Fixation B duration and 4.0 ms per 100 ms of Fixation A duration.

In the preceding analyses, the dataset has been restricted to cases where the eccentricity of the target from Fixation B was restricted to four characters or less. A comparable regression analysis of the cases where the eccentricity of the target from Fixation B is larger ($ECC_B > 5$) confirmed that the eccentricity from Fixation A had a similar effect size and direction as obtained for the ($ECC_B < 5$) data (see Table 1).

Next, the issue of whether preview benefit might accumulate across intraword saccades but not interword saccades was addressed by conducting separate regression analyses for the refixated and non-refixated patterns (see Fig. 1). Table 1 indicates largely comparable effects of eccentricity and time for these two subsets of the data. FFD decreased an average of 1.9 ms and 4.1 ms per character of eccentricity from Fixation A, for the non-refixated and refixated patterns, respectively. FFD increased an average of 10.4 ms/100 ms and 11.6 ms/100 ms of Fixation B duration, for the two type of pattern. The regression results for the non-refixated patterns differed from those for the refixated patterns in one respect. Although for the non-refixated patterns FFD increased an average of 2.9 ms/100 ms of Fixation A duration, there was no reliable unique influence of Fixation A duration for the refixated patterns. When the first fixation on the target word is preceded by two fixations on either word $n-1$ or $n-2$ (a refixation sequence; see Fig. 1), the duration of this fixation is not influenced by the duration of the first fixation of the refixation sequence ($p = 0.138$).

It is useful to verify that two other duration measures widely-used in reading research are also sensitive to the eccentricity from the penultimate fixation. Gaze duration (the sum of all fixations made on the target word before the eyes leave the word) and single-fixation duration (equivalent to FFD but where only a single fixation is made on the target) replaced FFD as the dependent variable in comparable repeated-measures regression analyses (all fixation patterns, $ECC_B < 5$ only). The results obtained using FFD were replicated: controlling for the other variables, gaze and single-fixation duration decreased an average of 3.8 ms and 2.7 ms per character of eccentricity from Fixation A, respectively. The two measures also increased an average of 12.6 ms/100 ms and 10.4 ms/100 ms of Fixation B duration, respectively, and increased 4.3 ms/100 ms and 3.6 ms/100 ms of the duration of Fixation A, respectively.

[4] This result is not consistent with Schroyens et al.'s (1999) finding. The possibility remains that the relatively large spillover effect has obscured any observable facilitation attributable to the time spent in the perceptual span.

Table 1
Results of repeated measures simultaneous multiple regression analyses conducted on various subsets of the data

	WL	ECC_B	FixDur B	ECC_A	FixDur A
Near only ($ECC_B < 5$)					
Mean	5.70	11.04	0.101	−2.80	0.040
$t(9)$	5.82	9.19	4.21	−4.47	4.57
p	<.001	<.001	.002	.002	.001
Far only ($ECC_B > 5$)					
Mean	3.88	3.28	0.104	−2.06	0.018
$t(9)$	6.04	2.22	3.51	−4.32	1.83
p	<.001	.054	.007	.002	.100
Non-refixated patterns only ($ECC_B < 5$)					
Mean	4.68	9.46	0.104	−1.94	0.029
$t(9)$	5.61	7.77	3.73	−3.02	2.16
p	<.001	<.001	.005	.014	.059
Refixated patterns only ($ECC_B < 5$)					
Mean	10.10	17.94	0.116	−4.11	0.073
$t(9)$	3.54	7.16	5.38	−3.45	1.63
p	.006	<.001	<.001	.007	.138

Across-participant means of unstandardised regression coefficients are shown, with corresponding one-sample t-test results. *Note*: WL = length of target word in letters; ECC_A = eccentricity, in character spaces, of the target word from Fixation A; ECC_B = eccentricity of the target from Fixation B; FixDur = fixation duration.

Finally, there is a possibility that the obtained negative relationship between ECC_A and FFD might still be due to some confound with the difficulty of processing one of the words previous to the target. For instance, if it were the case that when the eccentricity of the target word from Fixation A is small, processing of word $n-1$ tends to be more difficult than when eccentricity is large, then 'spillover' effects from $n-1$ could be responsible for the observed negative relationship. This was easily tested by including in a further regression analysis a strong correlate of the difficulty of processing word $n-1$: its frequency of occurrence (e.g., Rayner, 1998). If processing difficulty is modulating the effect, then once word frequency is partialled out no unique effect of ECC_A should remain. This was not the case, however; additionally incorporating frequency (computed from the 100 million-word British National Corpus) in the regression analysis (all fixation patterns, $ECC_B < 5$) indicated a small, significant effect of the frequency of word $n-1$ on FFD: mean $b = -1.229$, $t(9) = -2.69$, $p = .025$, but did not affect the role of ECC_A as a reliable predictor of FFD.

4. Summary

The data are not consistent with the accumulation of preview benefit across successive saccades. Although the anticipated positive linear relationship [5] between the FFD on the target and its eccentricity from Fixation B was obtained (explainable in terms of the amount of parafoveal preprocessing possible), preview benefit was also modulated by its eccentricity from two fixations previous, but in the opposite direction: the nearer the target from this fixation position, the longer the fixation. This effect occurred whether the previous fixation was near the target (less than five character spaces away) or further from the target (more than five character spaces back), and whether or not Fixations A and B occurred on the same word or on different words.

Parafoveal preview benefit is also modulated by time, but also in the opposite direction as expected: the longer the target word spends in the perceptual span, the longer its FFD. Probably the most coherent explanation for the effect of the duration of the penultimate fixation on the current fixation is not attributable to processing difficulty with spillover to the next fixation(s). Rather, successive fixations may be correlated in duration due to reading rhythm (cf. O'Regan, 1992), i.e., stretches of relatively fast or relative slow reading. A good analogy is walking speed: successive stride intervals are correlated even though difficulty of the terrain may cause large amounts of variability in walking speed.

One influential reading model, EZ-Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003), does not assume that preview benefit accumulates across multiple saccades; however, EZ-Reader would not predict the negative relationship obtained between the eccentricity of the target from the penultimate fixation and first fixation duration. The present findings represent a challenge for current and future computational models of eye movements in reading.

[5] As noted in Footnote 1, Rayner and McConkie (1976) did not observe a consistent positive relationship between progressive saccade length and fixation duration in a global analysis of eye movement data.

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